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F. R. NASH.

A STUDY OF THE MERCURY LINES WITH THE MICHELSON ECHELON GRATING.

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A STUDY OF THE MERCURY LINES WITH THE MICHELSON ECHELON GRATING

by

Francis Ralph Nash

A Thesis Submitted for the Degree of

BACHELOR OF PHILOSOPHY

UNIVERSITY OF WISCONSIN

1907

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INTRODUCTION.

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INTRODUCTION.

This paper is a description of the methods followed and the results obtained, in a study of the mercury lines, by means of the Michelson echelon diffraction grating. The simple theory of the grating is worked out with its special application to the Michelson echelon grating, and a description is given of the methods adopted for the determination of the constants of the instrument, and for the study of the mercury lines. The results obtained are compared with those of L. Janicki.[1] The light from a mercury arc of the Arons type was also tested to see if any Döppler effect could be observed.

The composition of the mercury lines has been investigated by a great many physicists with somewhat varying results. The subject has been taken up by O. Lummer[2], A. Hagenback and H. Konen[3], with the Rowland grating. Further investigations were made by Ch. Fabry and A. Perot[4] with their type of interferometer. The most concordant results have been obtained quite recently by

1 Annalen der Physik. Jan. 1906. 19 pp. 36-79.
2 Verhdl. d. deutschen phys. Ges. 1901. p. 95.
3 Zeitschr. f. wissensch. Photogr. 1 pp. 342-346,1903
4 Ann. de chim et phys. (7) 12.

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Gehrcke and Bayer[1] using an improved form of the Lummer interference spectroscope and by L Janicki[2] with a Michelson echelon grating.

The Döppler effect has been readily observed by Stark[3] and by Hull[4] using a canal ray tube filled with hydrogen. The evidence of the existence of the effect in the case of the mercury vapor was questionable.

1 Annalen der Physik 20, p. 269, 1906.
2 loc. cit.
3 Astrophysical Journal, Jan. 1907, pp. 23-44, and April, 1907, pp. 170-194.
4 Astrophysical Journal, Jan. 1907, pp. 1-22.

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GENERAL THEORY OF GRATING.

A grating is a surface having a periodical structure which impresses a periodical alteration of phase or intensity on a transmitted or reflected wave of light. A common method of making a grating is to rule lines parallel and equidistant, on a glass or metal surface.

In Fig. I, let A B be a transmission grating. The openings a_1 and a_2 etc. may be considered sources from which secondary Huyghen's wavelets are propagated. Let C D be a wave front. In order that the light at C D be in the same phase the optical distance $L_1 F_1 - L_2 F_2$ must equal some multiple of a wave length.

$$\sin \theta = \frac{LE}{e} = \frac{n\lambda}{e} \text{ ---------- } 1$$

n being some integer, λ the wave length of light, and e the distance between corresponding points in adjacent openings, i.e., the grating space.

There is more than one value of θ which will give a maximum, but the number of values is limited since $\sin \theta$ cannot be greater than one. Therefore n may be any positive integer such that the product $n \frac{\lambda}{e}$ is less than one. That is, n must be less than $\frac{e}{\lambda}$. The amplitude in the direction of the maxima is Nka, where N is the number of lines in the grating, a the

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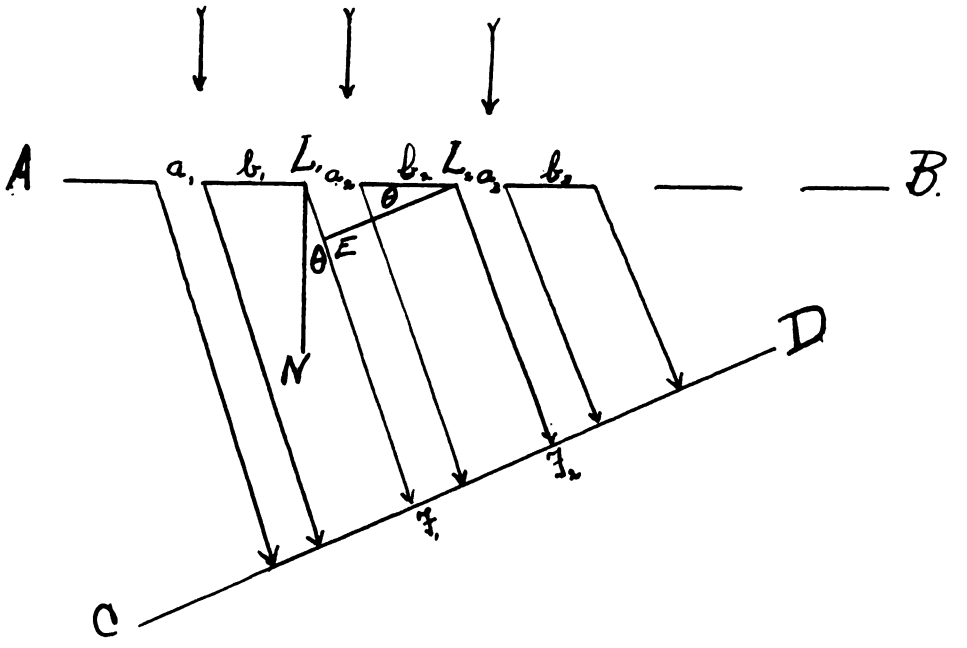
Fig 1.



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amplitude of the incident light, and k a constant depending on the direction and the shape of the grooves.

If the light which comes to the transmission grating does not strike perpendicularly upon the grating as represented in Fig. I, but makes an angle θ with the normal to the grating as represented in Fig. II, then the light coming from adjacent openings in the grating will experience a certain relative retardation.

In Fig. II, the retardation of the light ray R_2, over the light ray R_1, as they enter the grating is $e \sin \phi$. However, upon leaving the grating the light ray R_1 is retarded an amount equal to $e \sin \theta$ over the light ray, R_2. Therefore the resulting retardation is $e(\sin \phi - \sin \theta)$ which must equal some whole number of wave lengths if the light is to be in the same phase.

$$e(\sin \phi - \sin \theta) = n\lambda.$$

<u>Dispersive Power</u>: The equation $e \sin \theta = n\lambda$ gives the conditions for the light of wave length λ making the angle θ with the normal to the grating to be at a maximum upon reaching the screen. If there is a slight increment $\Delta\theta$ given to angle θ, this would cause a slightly different wave length $(\lambda + \Delta\lambda)$ to be at a maximum.

Therefore $e \sin(\theta + \Delta\theta) = n(\lambda + \Delta\lambda)$.

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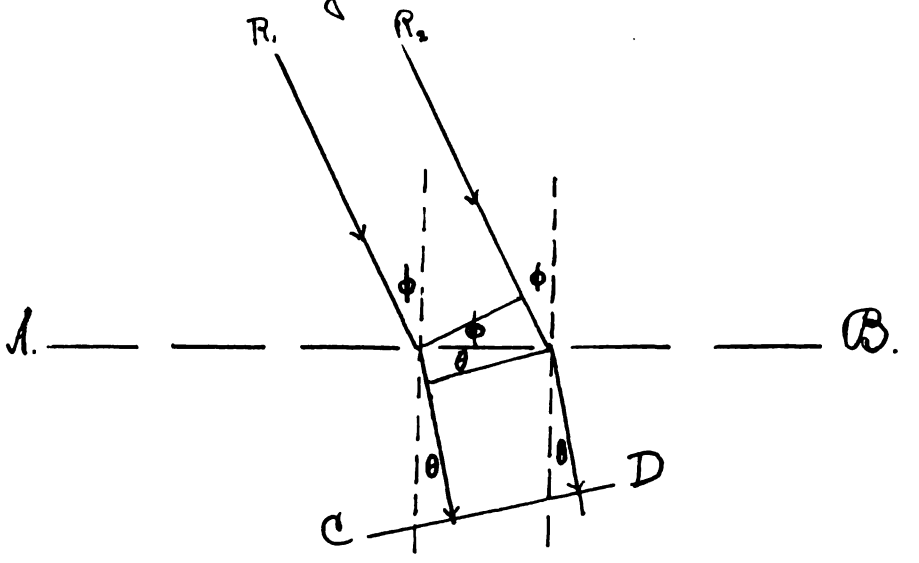
Fig II.



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Now by the dispersive power of a grating is meant the value of the limit of the ratio $\frac{\Delta\theta}{\Delta\lambda}$, or $\frac{d\theta}{d\lambda}$. By differentiating the equation $e \sin\theta = n\lambda$ with respect to λ

$$e \cos\theta \frac{d\theta}{d\lambda} = n$$

$$\frac{d\theta}{d\lambda} = \frac{n}{e \cdot \cos\theta} \quad \text{----------} \quad 2$$

This shows that the dispersive power of the grating is directly proportional to the order of the spectrum observed and inversely proportional to the distance between adjacent lines of the grating, and also inversely proportional to the cosine of the angle which the light leaving the grating makes with the normal to the grating.

<u>Resolving Power of a Grating</u>: In order that light containing wave lengths of λ and $\lambda + \Delta\lambda$ respectively may be separated so as to form distinct images upon the screen after passing thru the grating and being focussed by the lens the breadth of the diffraction band due to each wave length must be less than twice the distance from center to center of the two bands.

In Fig. 3 let AB be a grating and let DF represent the direction of the light which when focused by a lens gives a bright line. Let CE be perpendicular to DE. Then $DE = Nn\lambda$, where N is the number of lines in the grating

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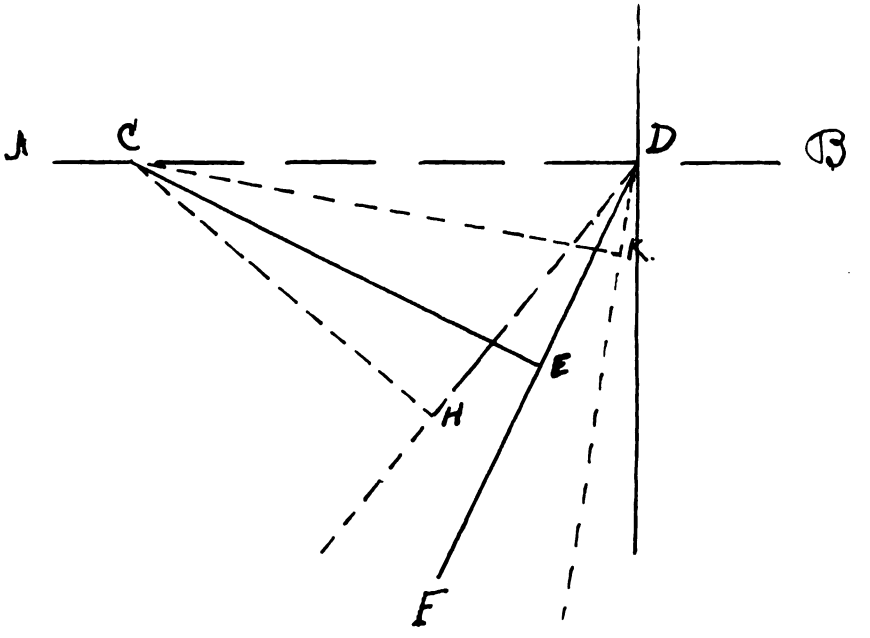
Fig 3.



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and n is the order of the spectrum formed. Let CH be so drawn that the perpendicular DH let fall from point D is equal to $(Nn + 1)\lambda$. Light from corresponding points of the two extreme openings in the grating traverse optical distances differing by $(Nn + 1)\lambda$ upon reaching the screen. Light from the first opening and the $\frac{N}{2}$ opening will be out of phase by a half wave length upon reaching the screen providing the number of lines in the grating is even. If the number of openings is odd the last one may be neglected. Thus the rays parallel to DH interfere destructively. Consequently, light of wave length equal to λ, will cease to be diffracted along DH, but will be diffracted along any line lying between DF and DH. Let CK be so drawn that the perpendicular DK let fall on it from D is equal to $(Nn - 1)\lambda$. Then by reasoning similar to that used above, it can be proved that light of wave length λ will just cease to be diffracted along the direction DK, but will be diffracted along all lines lying between DK and DF. Therefore the nth bright band corresponding to the wave length λ, will be formed by rays diffracted at angles lying between $(\theta - d\theta)$ and $(\theta + d\theta)$ where FD makes the angle θ with the normal to the grating, HD makes the angle $(\theta + \Delta\theta)$ and KD makes the angle $(\theta - \Delta\theta)$.

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DH is approximately equal to DE plus the circular arc of radius CE times the numerical value of $\Delta\theta$ expressed in radians.

Therefore $DH = DE + CE\Delta\theta$

But $DE = Ne \sin\theta$, and $CE = Ne \cos\theta$

$DH = Ne(\sin\theta + \cos\theta \cdot \Delta\theta) = (Nn + 1)\lambda$

In a manner similar to the above

$DK = Ne(\sin\theta - \cos\theta \cdot \Delta\theta) = (Nn - 1)\lambda$

From the last two equations by subtraction:

$2Ne \cos\theta \cdot d\theta = 2\lambda$

Solving for $d\theta$, $d\theta = \dfrac{\lambda}{Ne \cos\theta}$

By substituting in the last equation the value of $d\theta$ in equation No. 2

$$\frac{nd\lambda}{e \cos\theta} = \frac{\lambda}{Ne \cos\theta}$$

$$\frac{\lambda}{d\lambda} = Nn \text{ ----------} 3$$

The expression $\frac{\lambda}{d\lambda}$ is the resolving power of the grating. $d\lambda$ is the smallest difference of wave length between lines of a mean wave length equal to λ, which can be resolved in the nth spectrum of a grating containing N rulings. This equation gives the conditions where the maximum of light of wave length $\lambda + \Delta\lambda$ falls upon the first minimum of light of wave length λ.

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When $\frac{\lambda}{d\lambda} = \frac{Nn}{2}$ is taken as the resolving power, the physical meaning is that in the spectrum the minimum of light of one wave length falls upon the minimum of light of the other wave length, thus giving a very distinct line in the spectrum for the light of each wave length.

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THE ECHELON GRATING.

It has already been shown that the power of a grating to separate different wave lengths of light and form distinct lines in the spectrum is directly equal to the product of the order of the spectrum observed and the number of rulings in the grating. With a ruled grating the spectra of the higher orders are so faint that they cannot be used to any great advantage. As the number of rulings is increased the order of spectrum which can be used is decreased, thus decreasing the effectiveness which would otherwise be realized by increasing the number of rulings. Gratings have been ruled with as many as 40,000 lines to the inch. All of these lines have to be similar, parallel, and equidistant, making the ruling of a grating very difficult, and the extent to which it could be carried limited.

The Michelson echelon grating is a type of transmission grating so constructed that spectra of very high orders can be observed, thus giving the instrument an enormous resolving power. This grating is made up of a great number of similar plates of glass built up in steps as represented in Fig.4. The plates are all of equal thickness, the steps are of equal width, and they are all

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Fig 4

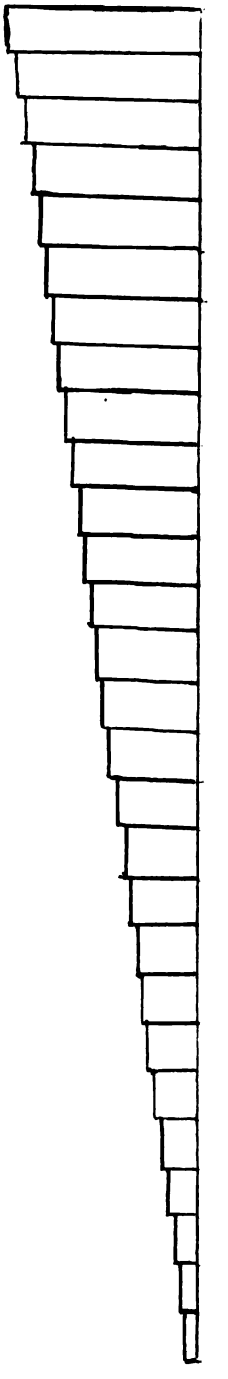
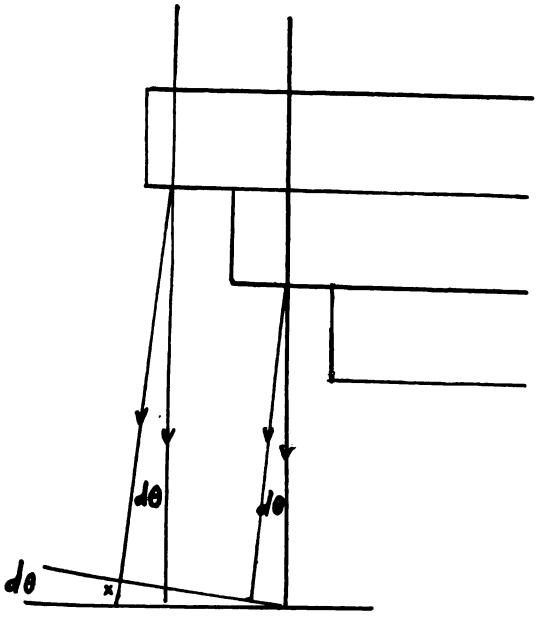


Fig. 5



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made from the same kind of glass.

In Fig. 5 light enters at corresponding points on adjacent steps of the grating. The optical path of one ray is $(\mu t - t)$ greater than that of the other, where t is the thickness of the plates and μ is the optical density of the glass of which the plates are made. This difference in optical path must equal some whole number of wave lengths if the light from the two sources is to be in the same phase upon reaching WF.

$$(\mu - 1)t = n\lambda.$$

If light having a wave length λ' and a refractive index of μ^1 enters the grating it will upon leaving the grating make an angle $d\theta$ with the rays of wave length λ and refractive index μ. Since where angles are very small, the numerical value of the angle measured in radians may be placed equal to the tangent of the angle $d\theta = \frac{x}{e}$. The retardation is $(\mu^1 - 1)\ t - x$ which equals $n\lambda'$.

$$(\mu' - 1)\ t - x - (\mu - 1)\ t = n\lambda' - n\lambda$$

$$\text{or } -x = n(\lambda' - \lambda) - (\mu' - \mu)\ t$$

$$d\theta = \frac{x}{e} = \left[n(\lambda - \lambda') - (\mu - \mu')\ t\right]/e$$

$$\frac{d\theta}{d\lambda} = \left[n - \frac{(\mu - \mu')t}{(\lambda - \lambda')}\right]/e \text{ ---------- } 4$$

It has already been shown that two wave lengths λ' and λ can be resolved and made to form separate images

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in the spectrum when the first maximum of the diffracted image of one falls upon the first minimum of the other. It has also been shown in the discussion on Theory of the Grating, that this takes place when the total retardation of the rays coming from the outer edges of the grating is one wave length greater for λ than for λ' or vice versa. The total width of the echelon grating is eN, where N is the number of plates and e is the width of each step. Then the total relative retardation of one wave length over another wave length must equal $Ne\, d\theta = \lambda$ from which $\frac{d\theta}{\lambda} = Ne$. Multiplying equation (4) by this last equation,

$$\frac{\lambda}{d\lambda} = N\left(n - \frac{d\mu}{d\lambda}t\right)$$

The right hand member of the last equation is approximately equal to Nn. This proves that the formula for the resolving power of a ruled grating, which has been proved in the discussion on theory of grating, holds good for the Michelson's echelon grating.

Therefore, $\frac{\lambda}{d\lambda} = Nn$

The physical meaning of the last equation is that $d\lambda$ is the smallest difference of wave length which light of two different wave lengths λ and λ' may have, and be resolved in the nth order of a grating with N plates. It also shows that the resolving power is directly proportional to the number of plates of which the grating is

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composed and the order of the spectrum observed. The order of the spectrum has been shown proportional to the thickness of the plates, therefore the resolving power is proportional to the total thickness of glass.

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EXPERIMENTAL.

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CONSTANTS OF APPARATUS.

Number of plates in grating,---------- 32

Number of steps in grating,---------- 33

The optical density and thickness of the plates were determined by the microscope method.

The optical density μ is approximately for white light,----------1.54

The thickness of the plates is,----------7.24 m.m.

The order of the spectra formed by this grating may be roughly determined by the formula $(\mu - 1)t = n\lambda$ which has already been developed. Substituting in this formula the values above determined for μ and t, and placing $\lambda = .6 \times 10^{-3}$ m.m. which is roughly the wave length of the D lines

$$(1.54 - 1)\ 7.24 = n \cdot .6 \times 10^{-3}$$

$$n = \frac{(1.54-1)7.24}{.6 \times 10^{-3}} \text{ ---------- } 6516$$

In a similar manner the resolving power of the grating may be calculated, by substituting in the formula $\frac{\lambda}{d\lambda} = Nn$, which has also been developed, the respective values for N, n, and λ. For the grating used N = 33, n = 6516, and λ may be taken equal to .0006 m.m.

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$$\frac{\lambda}{\Delta\lambda} = 33 \times 6516 \text{ ---------- } 215028.$$

The smallest difference in wave length which two waves can have and still be resolved by the grating may be determined by solving the equation for $\Delta\lambda$.

$$\Delta\lambda = \frac{.0006}{33 \times 6516} \text{ ---------- } .00000000279 \text{ m.m.}$$

The Ångstrom unit expressed in millimeters equals .0000001. Therefore the ratio of $\Delta\lambda$ to the Ångstrom unit is less than three hundredths.

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STUDY OF THE MERCURY LINES.

The echelon was first used to analyze the light from the mercury arc. The arc was of the Arons type and operated on about eight amperes direct current. The apparatus was arranged as represented in Fig. 6. The mercury arc was so placed that rays of light from it entered the collimator at the slit s, after passing thru the lens. These rays were rendered parallel by the collimator, and then passed into the echelon grating. From the grating the light passed thru a prism from which it entered the telescope. The prism served to separate the light from the mercury arc into its seven principal lines: the orange lines λ = 5790 and 5769 Å. E., bright green λ = 5461 Å. E., faint green λ = 4916 Å.E., purple λ = 4358 Å.E., and violet λ = 4078 and 4047 Å.E.

The telescope was so mounted that by turning it any line desired could be brought into view. Then by adjusting the prism so that it was in its position of minimum deviation, and focusing the telescope, these lines became distinct. Each was so resolved by the grating that it was found to be composed of several wave lengths differing sufficiently one from the other so as to form separate

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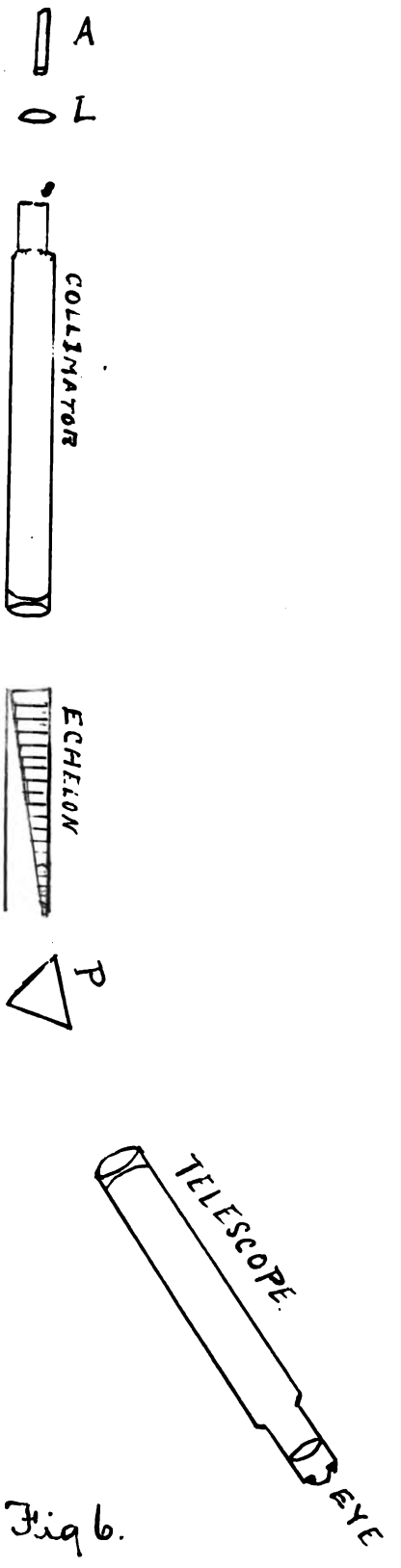

Fig 6.

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lines.

The orange lines were studied first and with the apparatus arranged as shown in Fig. 7, the light could be separated into the two distinct lines by means of a prism and two lenses before it passed into the collimator. This system containing the slit, lenses, and prism was then so arranged that first one and then the other of the narrow orange lines could be thrown into the grating by moving one of the lenses, which was conveniently mounted so as to be adjusted by means of a screw. Within the grating the lines were further resolved so that the components could be clearly separated.

Number 1 of the accompanying plate represents the resolution of line $\lambda = 5790$. This corresponds thruout with that of L. Janicki which is reproduced in the plate and labeled 1.J. The light which forms these lines is made up of four components differing in wave length sufficiently to be resolved by the grating. By a slight readjustment of one of the lenses the orange of wave length $\lambda = 5769$ replaced the first orange. Number 2 is a drawing of the line as formed by this light. The light is all of so nearly the same wave length that but the one distinct line could be detected in the nth order. Janicki's drawing shows but the one line.

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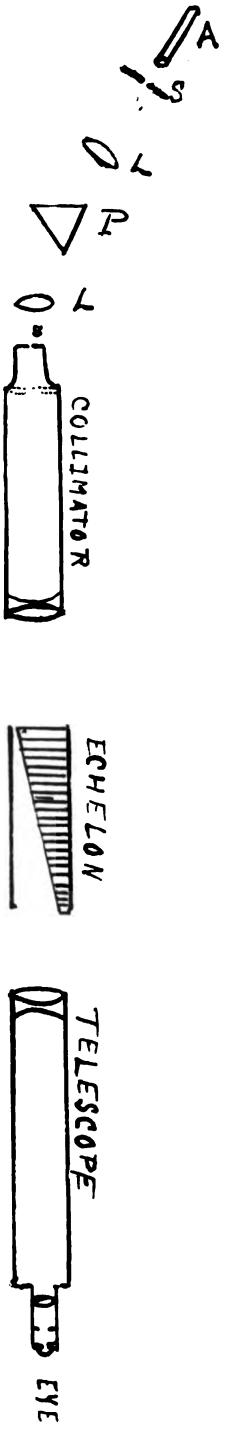

Fig 7.

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Number 3 represents the spectrum formed by the strong green λ = 5461. This line is made up of at least five components which were separated by the grating. The intensity of each component is shown in the diagram by making the line representing the component correspondingly heavy. This spectrum differs from that of Janicki only in that the components differ slightly in arrangement due to the constants of the apparatus.

Number four represents the faint green line λ = 4916 which is nearly midway between the light green and the purple. This line was quite faint and the grating did not bring out more than the one wave length. Janicki gives no diagram of this line.

Number 5 is a drawing of the line of wave length λ = 4358. The two outer and dark lines are different orders of the same wave length of light. This light is composed of five components differing in wave length sufficiently to be separated. At times it seemed as tho the outer dark lines were split; if so this light is made up of six components, two components of great intensity and four of comparatively less intensity. Janicki's spectrum for this light is indistinct and blurred but his explanation states that he succeeded not only in separating the two inner lines each into two separate lines, but he also

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succeeded in splitting the outer heavy lines. Thus his spectrum brings out six components.

Numbers 6 and 7 are drawings of the spectrum formed by the faint violet of wave lengths λ = 4078 and 4047 respectively. This light was quite faint and considerable difficulty was experienced in admitting each line separately into the grating.

The same arrangement of apparatus, Fig. 7, as was used in separating the orange lines, was made to serve the purpose here. When the lenses, the slit, and the prism were properly adjusted relative to one another, the mercury arc and the slit of the collimator leading to the grating, two very faint fine lines, barely separated, could be seen. Then by readjusting one of the lenses, these lines could be thrown one at a time into the grating where they were further resolved. Number 6 is the drawing for wave length λ = 4078. The grating did not bring out more than the one component, two orders of which are shown. Janicki's diagram for this spectrum shows first three faint components in addition to the one principal component. Number 7 is a drawing of the spectrum formed by light of wave length λ = 4047. The grating resolved this light into three components, one being of

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much greater intensity than the other two. The figure shows two orders of the component of greatest intensity and one order each of the components of lesser intensity. The fainter components are found one on each side of the components of greatest intensity. Janicki brings out one faint component in addition to the ones above mentioned.

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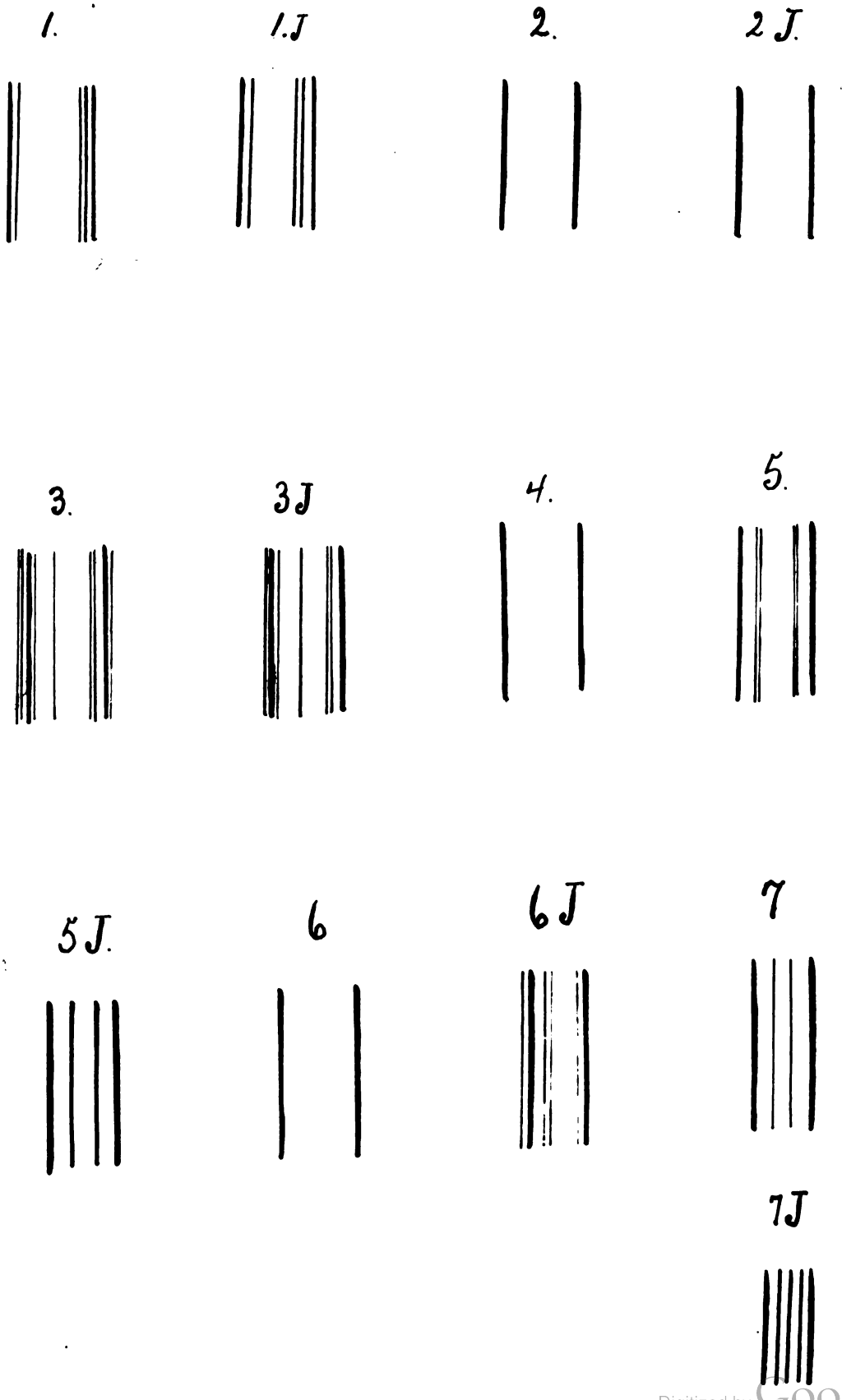

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TEST FOR DÖPPLER EFFECT IN MERCURY ARC.[1]

The Döppler effect can be best explained by reference to this phenomenon in sound. If a source of sound is caused to move rapidly toward a listener, more sound waves will reach the ear of the listner in a second of time than where the source remains stationary. That is, the period is given a negative increment. Now the wave length λ, the period T, and the velocity V, are connected by the following relation: $VT = \lambda$. If T is given an increment, λ will be decreased, and $V(T + \Delta T) = (\lambda + \Delta\lambda)$, where the corresponding increments are of the same sign. Since the pitch of a note is inversely proportional to the wave length, the listener will experience a rise in the pitch when the source is moving toward him and $\Delta\lambda$ is negative, and a fall in pitch when the source is moving away and $\Delta\lambda$ is positive. Edser[2] states the law as follows: "Relative motion between an observer and a source of wave disturbance increases or decreases the apparent period of the emitted waves, according as the motion increases or decreases the distance between source

[1] Edser's Light for Students, pp. 350-357.
[2] Edser's Light for Students, p. 351.

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and observer." The amount of this change depends upon the rate of relative motion.

The Döppler phenomenon has been observed in light. According to this principle, if a star is moving away from the earth, the wave length of radiations emitted by the star should be longer than if the star were stationary. If the star were moving toward the earth the spectral lines should be displaced toward the violet end of the spectrum . In 1868 Dr. Huggins found this to be true. He discovered that in the spectrum of Sirius the F line was slightly shifted toward the red end of the spectrum. This indicated that Sirius is moving away from the earth. The exact amount of the shift was measured and the amount of relative motion between the earth and Sirius calculated.

The aim in the following experiment is to determine whether or not the light emitted by the mercury arc is affected by this phenomenon. That is, to determing whether the passage of the current thru the arc gives to the vibrating particles a directed motion of such magnitude that its Döppler effect can be observed. If so, reversing the current thru the arc would cause a shift in the lines formed in the spectrum.

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Fig. 8 shows the arrangement of apparatus for this experiment. The arc was operated on about 8 amperes direct current. Mirrors were so arranged as to reflect the light from the two ends of the arc, thru lenses, and then to second mirrors so placed as to cause the light to make an angle of 90°. From the last mirrors the light passed thru glass prisms and was totally reflected from the back surface of each prism, so as to enter the slit of the collimator leading to the grating, in parallel beams. The prisms reflecting the light were placed one over the other, so that the spectrum formed by the light coming from one end of the arc would be located just above the corresponding spectrum formed by the light coming from the other end of the arc. After passing thru the grating the light entered a prism which separated it, forming the principal lines. These lines were then studied. The light from the two sources formed continuous lines and the components of each principal line were also continuous. The direction of the current thru the mercury arc was then reversed by means of a commutator and the position of the components in each line observed. There was no appreciable shift in any instance and only a slight shading showed where the upper spectrum united with the lower.

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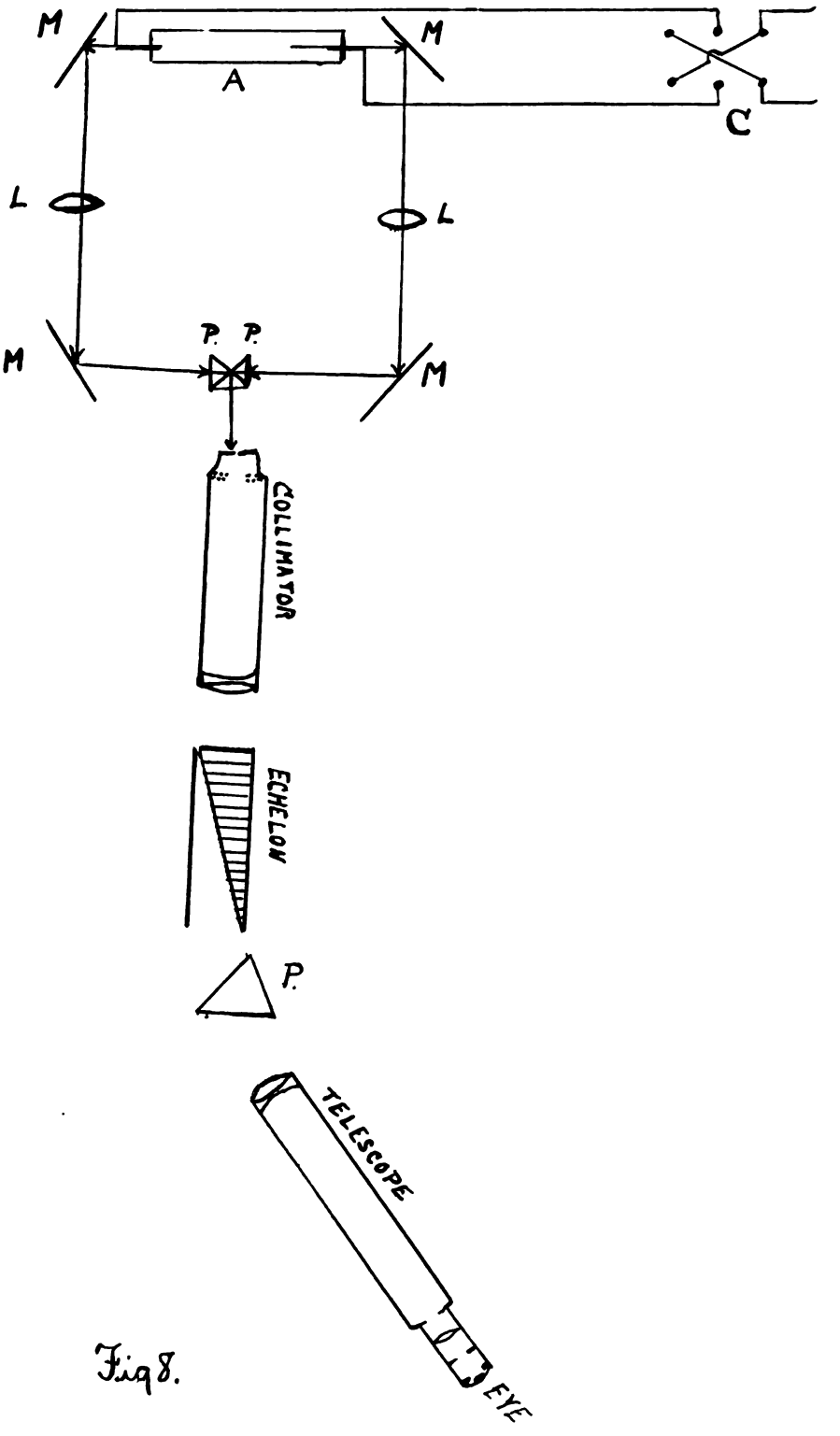

Fig 8.

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The conclusion reached is that the period of vibration of the light coming from one end of the arc is not increased or decreased over the period of the corresponding light coming from the other end of the arc, sufficiently for its Döppler effect to be observed. In other words, the linear velocities of the vibrating ions are relatively small.

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Approved by

L. R. Ingersoll, Prof. in Physics.
June 13, 1907.

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